SHAMROCK SURFACTANTS AND THEIR METHODS OF USE

By David A. Jaeger

This application claims priority under 35 U.S.C. §119(e) to US Provisional Application No. 60/495,214, filed on August 13, 2003, the entire contents of which are incorporated by reference herein.

Pursuant to 35 U.S.C. §202(c), it is hereby acknowledged that the U.S. Government has certain rights in the invention described herein, which was made, at least in part, with funds from the Department of Defense.

FIELD OF THE INVENTION

The invention relates to surfactants, referred to herein generally as "shamrock surfactants", which have a variety of applications, including without limitation, chemical decontamination of mustard, storage and release devices, chemical switches and remediation of water contaminated with heavy metal ions.

Shamrock surfactants have the general structure **1**. The darkened circles represent charged and/or polar nonionic head groups, and the wavy lines, hydrocarbon chains. Thus the surfactants contain two outer head groups connected to a central head group by hydrocarbon chains. The term "shamrock" denotes their triple-headed character, reflecting the fact that shamrocks have leaflets in groups of three.

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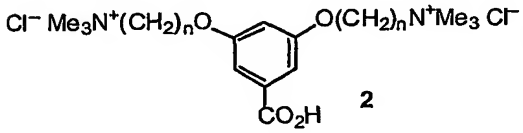
BACKGROUND OF THE INVENTION

Surfactants are important in a broad spectrum of applications as diverse as oil recovery[1] and drug delivery[2]. Over the past few years there has been increasing activity in the synthesis of novel functionalized and unfunctionalized surfactants, which has been driven by a variety of factors.[3] For example, many new surfactants have been designed for specific applications, and others have been synthesized in a search for novel and interesting properties. The former include cleavable surfactants[4,5] and the latter, gemini surfactants.[6]

The synthesis of novel surfactants and the characterization of their properties, even without preconceived applications, are indeed worthwhile endeavors, as evidenced by the success of gemini surfactants. They have been shown to have unique physical properties, compared to conventional surfactants, and have been used to advantage in a number of important applications, such as skin care formulations, antibacterial regimens, and the preparation of high-porosity materials.

F. M. Menger has reported surfactants **2** (n = 8, 12, and 16),[8] which, upon ionization of their carboxyl groups, may considered analogous to shamrock surfactants. Other known surfactants such as **3**[9] and **4** (n = 10, 12, 14, 16)[10] contain three head groups, but they are not shamrock surfactants. The major lipophilic character of surfactants such as **3** is provided by three alkyl chains, whereas that of shamrock surfactants **1** is provided only by the two hydrocarbon chains linking the three head groups. Shamrock surfactants are structurally related to, but are more complex than, bola

surfactants, which contain two head groups connected by one or more hydrocarbon chains, as in **5**.[11] Also related, but structurally distinct, are hyperextended surfactants, such as **6**,[12] and ionene polyelectrolytes, such as **7** (n = ca. 30).[13]



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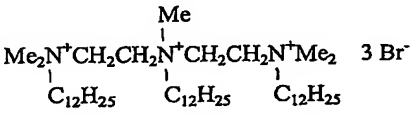

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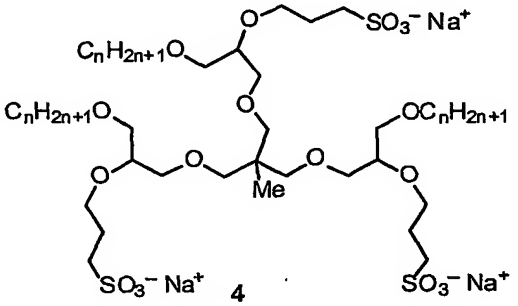

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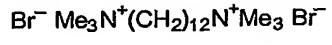

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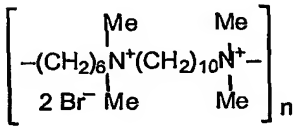

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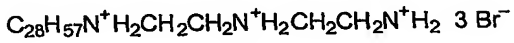

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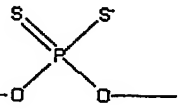
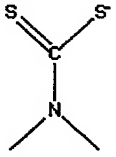
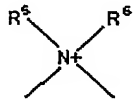
SUMMARY OF THE INVENTION

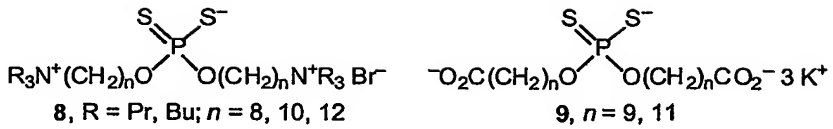
In accordance with one aspect of the present invention, there is provided a surfactant compound of the formula:

$$[X\text{-}L\text{-}Z\text{-}L'\text{-}X'](A)p \qquad (I)$$

wherein X and X' represent outer head groups, which may be the same or different and comprise charged moieties selected from the group of $-N^+R^1R^2R^3$, R^1, R^2 and R^3 being the same or different and representing hydrocarbyl groups, $-CO_2^-$ or $-O(CH_2)_mSO_3^-$, m being an integer from 2 to 30, or polar moieties of the formula, $-O-(CH_2CH_2O)_n-R^4$, R^4 being a C_1-C_6 hydrocarbyl group and n is an integer from 1 to 1000; L and L' are the same or different and represent a hydrocarbon linking moiety which may

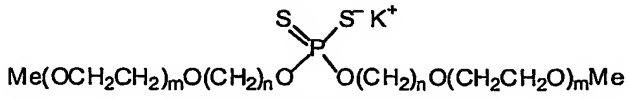
optionally be interrupted with oxygen; Z represents a central head group selected from a dithiophosphate moiety,  , a dithiocarbamate moiety,  , or a quaternary ammonium moiety,  , wherein R^5 and R^6 are the same or different and represent C_1-C_6 hydrocarbyl groups, with the proviso that when Z represents the aforementioned dithiocarbamate moiety or said quaternary ammonium moiety, X and X′ do not represent $NR^1R^2R^3$, and with the further proviso that X and X′ do not represent $-O(CH_2)_mSO_3-$ unless Z represents said quaternary ammonium moiety; and A represents a counter ion, which may be either positive or negative depending on the net charge of [X-L-Z-L′-X′] and p is an integer which when multiplied by the valency of said counter ion yields the absolute value of the net charge of [X-L-Z-L′-X′].

One series of shamrock surfactants, in accordance with the invention, comprises Phosphorodithioate (Dithiophosphate)-Based Surfactants and includes surfactants **8-10**, which contain a central (nucleophilic)[14] dithiophosphate group. In addition, **8**, **9**, and **10** contain two cationic, two anionic, and two polar nonionic head groups, respectively, resulting in net charges of 1^+, 3^-, and 1^-, respectively, for their organic units.



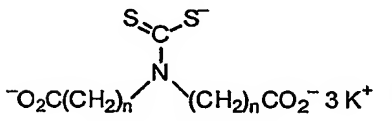
8, R = Pr, Bu; *n* = 8, 10, 12

9, *n* = 9, 11

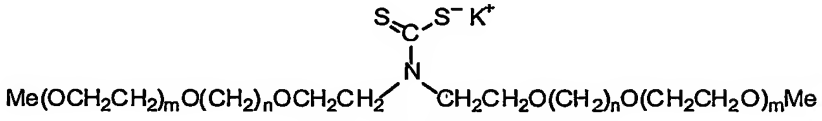


10 , m = 8, 10; *n* = 8, 10, 12

Another series of shamrock surfactants comprises Dithiocarbamate-Based Surfactants and includes surfactants **21** and **22**, which contain a central (nucleophilic)[14] dithiocarbamate group. In addition, **21** and **22** contain two anionic and two nonionic head groups, resulting in net charges of 3^- and 1^-, respectively, for their organic units.

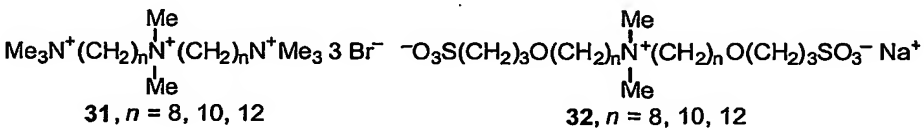


21, n = 7, 9, 11



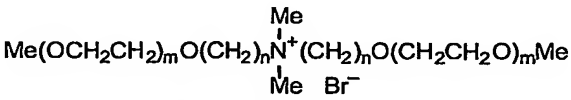
22, m = 8, 10; n = 8, 10, 12

A further series of shamrock surfactants comprises Quaternary Ammonium-Based Surfactants and include surfactants **31-33**, which contain a central quaternary ammonium group. In addition, **31**, **32**, and **33** contain two cationic, two polar anionic, and two nonionic head groups, resulting in net charges of 3^+, 1^-, and 1^+, respectively, for their organic units.



31, *n* = 8, 10, 12

32, *n* = 8, 10, 12



33, *m* = 8, 10; *n* = 8, 10, 12

In accordance with another aspect of this invention, there is provided a process for the chemical decontamination of mustard (i.e. $ClCH_2CH_2SCH_2CH_2Cl$), which involves reacting mustard with aggregates of a surfactant compound of the above-described formula (I), above, wherein the central head group is a dithiophosphate moiety or a dithiocarbamate moiety, under conditions causing a residue of mustard to be chemically bound to the surfactant compound by a nucleophilic substitution reaction, thereby producing the desired decontamination.

An important practical advantage of this method, as compared to known mustard decontamination methods involving nucelophilic substitution reactions, is that the decontaminated mustard becomes part of a surfactant. This feature can be exploited in water remediation. The derived aggregated surfactant, containing the mustard residue, can be removed from the aqueous reaction mixture by ultrafiltration. Such a filtration will retain aggregated surfactant, while allowing water to pass through the filter. Overall, the decontamination process, followed by ultrafiltration, will result in remediation of water that has been contaminated with mustard.

The present invention also provides a method for controlling release of a material contained or stored within a surfactant aggregate. This method comprises the steps of: a) providing an aggregated surfactant composed of at least one surfactant compound of formula (I) above, in which the central head group is a dithiophosphate moiety or a dithiocarbamate moiety, with the material being contained within the aggregated surfactant; and b) oxidizing the aggregated surfactant,

thereby producing a disulfide-linked dimer composed of the surfactant compounds, and releasing the material from the surfactant aggregates.

In one embodiment of the controlled-release method of the invention, the aggregated surfactant is composed of a surfactant compound wherein the central head group is a dithiophosphate moiety as described above, the linking moieties are the same straight or branched chain hydrocarbon moieties having 6 to 30 carbon atoms and the outer head groups are the same $-NR^1R^2R^3$, $-CO_2^-$ or $-O-(CH_2CH_2O)_n-R^4$ group, R^1, R^2 and R^3 being the same or different and representing hydrocarbyl groups, R^4 being a hydrogen or a C_1-C_6 hydrocarbyl group and n is an integer from 1 to 1000.

According to another embodiment of the controlled release method of this invention, the aggregated surfactant is composed of a surfactant compound wherein the central head group is a dithiocarbamate moiety, the linking moieties are the same straight or branched chain hydrocarbon moieties having 6 to 30 carbon atoms or straight or branched chain hydrocarbon moieties having 6 to 30 carbon atoms which are interrupted with oxygen, and the outer head groups are the same $-CO_2^-$ or $-O-(CH_2CH_2O)_nR^4$ group, R^4 being hydrogen or a C_1-C_6 hydrocarbyl group and n is an integer from 1 to 1000.

According to a further aspect of this invention, there is provided a process for removing heavy metal ions from a liquid medium containing same. This method comprises adding to the liquid medium a shamrock surfactant as described above, in an amount effective to form aggregates comprising the surfactant compound complexed with the heavy metal ions. Thereafter, the

liquid medium is filtered to separate the resulting aggregates from the liquid medium.

The process for removing heavy metal ions from a liquid medium in accordance with this invention may include the further step of oxidizing the aggregates in a reaction medium to release the heavy metal ions, thereby forming aggregates comprising dimers composed of the surfactant compounds linked through their central head group; and separating the resulting dimer-containing aggregates from the reaction medium, so that the surfactant compound can be regenerated from the dimers and recycled to the process.

Previously, metal ions have been removed from water by micellar-enhanced ultrafiltration (MEUF), as well as by ligand-modified MEUF. Generally, MEUF involves electrostatic binding of metal cations to anionic micelles/aggregates of surfactants such as sodium dodecyl sulfate. Ligand-modified MEUF involves a host micelle/aggregate containing a lipophilic ligand that coordinates to metal ions. Shamrock surfactants, however, offer a superior type of ligand-based separation process. With shamrock surfactants, no host surfactant is required, because the aggregate-forming surfactant also contains the ligand. Also, as noted above, the use of shamrock surfactants allows for their regeneration and recycling in the water remediation process.

BRIEF DESCRIPTION OF THE DRAWING

Figure 1 is an image obtained by phase contrastoptical microscopy of aggregates formed by Surfactant **8** with R=Bu, n=10, and NO_3^- exchanged for Br^-. Scale bar = 50 μm.

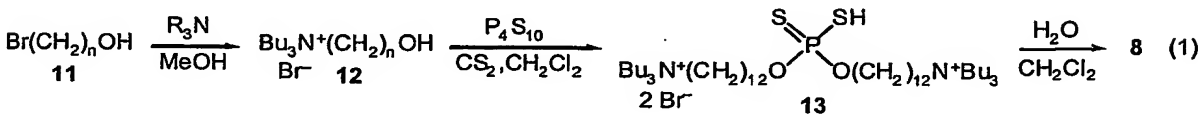
DETAILED DESCRIPTION OF THE INVENTION

The term "hydrocarbyl", as used herein, refers to an unsubstituted or substituted, saturated or unsaturated hydrocarbon radical containing from about 1 to 30 carbon atoms, which may be an aliphatic, cycloaliphatic or aromatic hydrocarbon group. When substituted, hydrocarbyl groups may be substituted at any available point of attachment. When the hydrocarbyl group is said to be substituted with a hydrocarbyl group, this is used interchangeably with "branched hydrocarbyl group". Exemplary unsubstituted hydrocarbon radicals include alkyl groups such as methyl, ethyl, propyl, isopropyl, n-butyl, t-butyl, isobutyl, pentyl, hexyl, isohexyl, heptyl, 4,4-dimethylpentyl, octyl, 2,2,4-trimethylpentyl, nonyl, decyl, undecyl, dodecyl, octadecyl, nonadecyl, eicosyl, heneicosyl, docosyl, tricosyl, tetracosyl, pentacosyl, and the like; alkenyl groups such as vinyl, allyl and the like; aromatic groups such as phenyl, tolyl, xylyl, napthyl, biphenyl, and the like; aralkyl groups such as benzyl, phenethyl, phenpropyl, phenbutyl, phenhexyl, napthoctyl, and the like; and cycloalkyl groups such as cyclopropyl, cyclobutyl, cyclohexyl, cycloheptyl, cyclooctyl, and the like. Exemplary substituents may include but are not limited to one or more of the following groups: halo (such as F, Cl, Br, I), alkoxy, alkylthio, hydroxy, carboxy (-COOH), amino ($-NH_2$), monoalkylamine (-NHR), dialkylamine ($-NR_2$), or thiol (-SH), wherein R in the aforementioned substituents represents a hydrocarbyl radical. Hydrocarbyl groups may also be interrupted with at least one oxygen, nitrogen, or sulfur atom.

The term "hydrocarbon linking moiety", as used herein, refers to a divalent hydrocarbon moiety of 6 to

30 carbon atoms in length, which may be saturated or unsaturated.

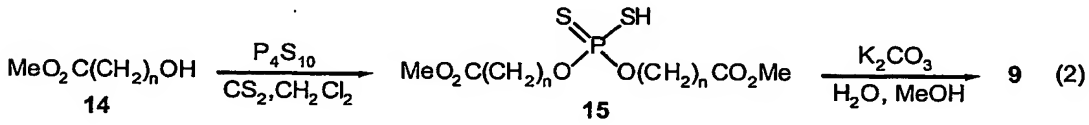
Surfactants **8**, which are mentioned above, may be synthesized in three straightforward steps as illustrated (eq 1), starting from commercially available (Aldrich) bromo alcohols 10 (n = 8, 10, 12). The nucleophilic substitution reaction of R_3N (R = Pr, Bu) with **11** will give **12**.[15] Then **12** may be converted into acid **13** by reaction with phosphorus pentasulfide, according to modified literature procedures.[16] Finally, a dichloromethane solution of **13** will be washed with water to give **8**. In this process, the dithiophosphoric acid unit of **13** undergoes ionization, with the net loss of HBr. [The pKa of $(MeO)_2PS_2H$ = 1.55 in 93:7 H_2O-EtOH.[17]] Surfactants **8** preferably contain propyl or butyl groups on their quaternary ammonium nitrogens instead of methyl groups, which are generally used as the short-chain components of quaternary ammonium surfactants. Methyl-substituted quaternary ammonium groups would be more susceptible to the possibility of S_N2 substitution at the methyl carbon by the nucleophilic dithiophosphate head group.[14] Average relative rates for alkyl substrates in S_N2 reactions are Me (30); Et (1); Pr (0.4); Bu (0.4).[18] In preliminary work, we have prepared two shamrock surfactants: **8** with R = Bu and n = 10; and **8** with R = Bu, n = 10, and NO_3^- exchanged for Br^-.[19]



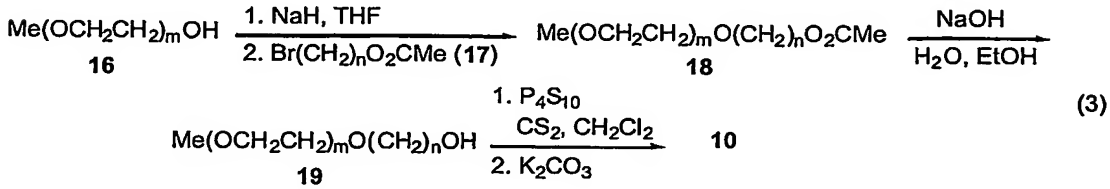
(1)

Surfactants **9** may be synthesized as illustrated (eq 2), starting with **14** (n = 9, 11), which is obtained by

Fischer esterification of the corresponding commercially available (Aldrich) ω-hydroxy carboxylic acids. There is a potential complication in the conversion of **14** into **15**, namely the possibility of the reaction of **14**'s ester group with P_4S_{10}. It is known that esters of carboxylic acids can be converted into thiocarboxylic *O*-esters [RC(=S)OR'] with P_4S_{10}, but the yields are typically very low (ca. 10%).[20] With use of the (normal) stoichiometric amount of P_4S_{10} in its reaction with **14**,[16] this undesirable side reaction should be precluded. The conversion of **15** into **9** by basic hydrolysis of its carboxylic ester groups may be straightforward, given the stability of the dithiophosphate group (see below).

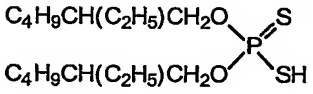


Surfactants **10** may be synthesized as illustrated (eq 3), starting with known polyethylene glycol monomethyl ethers **16** (m = 8, 10),[21] which may be prepared according to their literature procedures.[21] The alkylation of **16** with bromo ester **17** (n = 8, 10, 12), prepared by the acetylation of **11**, will give **18**. Then **19**, obtained by hydrolysis of **18**, may be converted into surfactants **10**.



The dithiophosphate groups of **8-10** almost certainly would be stable with respect to hydrolysis in water,

based on literature precedent.[22] No hydrolysis of the sodium salt of **20** was detected during 134 h at 65°C in 4 M NaOH. On the other hand, acid **20** itself hydrolyzes under forcing conditions. At 65°C, **20** underwent ca. 50% hydrolysis during 24 h in contact with water or 4 M hydrochloric acid. But at 25°C, **20** underwent <10% hydrolysis during 5 months in contact with water or 1 M hydrochloric acid.[22]



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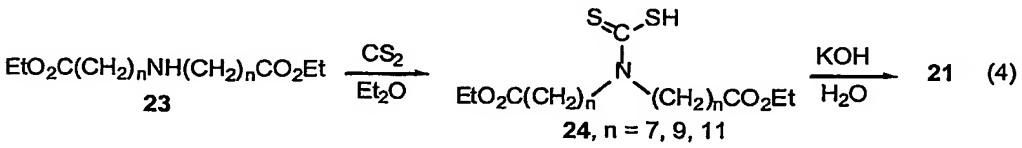
Surfactants **21** may be synthesized as illustrated (eq 4), starting with diester amines **23** (n = 7, 9, 11), which may be prepared by the literature procedure[23] for the known homologue with n = 5. The reaction of **23** with carbon disulfide to give **24** may be performed according to modified literature procedures[24] that we have successfully applied to the synthesis of other dithiocarbamate surfactants.[25] Then **24** may be subjected to basic hydrolysis of its ester groups and deprotonation to give **21**.



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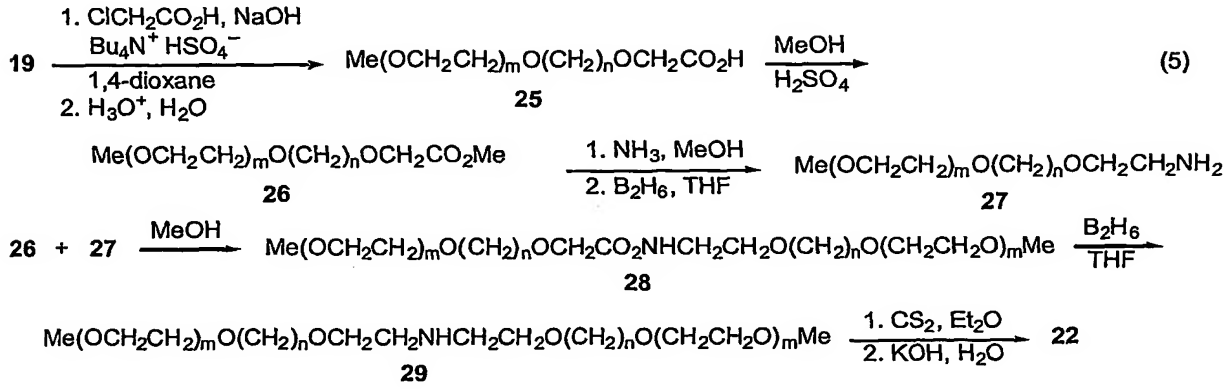
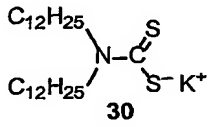
24, n = 7, 9, 11

Surfactants **22** may be prepared as illustrated (eq 5). The alkylation of alcohol **19** (see eq 3) with chloroacetic acid according to a literature procedure[26] for a related compound may give acid **25** (m = 8, 10; n = 8, 10, 12), which may be converted into amine **27** through ester **26**. Then, the reaction of **26** and **27** will yield

amide **28**, which may be reduced to amine **29**, followed by its conversion[24,25] into **22**.



The anionic dialkyldithiocarbamate groups of **21** and **22** are expected to be stable over extended periods (days) in water at pH >7, based on literature precedent.[27,28,29] Solid **30**, which was prepared by a route analogous to those above, was unchanged after an extended period at 23°C.[25] The pK_a of *N,N*-diethyldithiocarbamic acid is 4.04.[30a]



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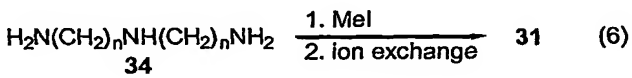
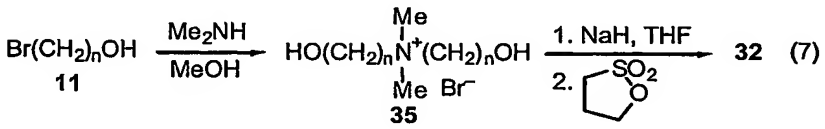
Surfactants **31** may be synthesized as illustrated (eq 6), starting with triamines **34** (n = 8, 10, 12), which may be prepared by the literature procedures[31] employed for such triamines. Ion exchange is effective to replace iodide by bromide.

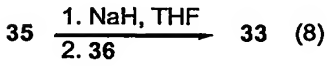


Surfactants **32** may be synthesized as illustrated (eq 7). The quaternization of dimethylamine with bromo

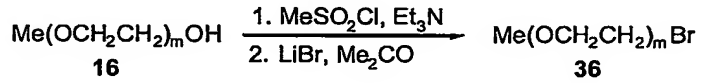
alcohols **11** (n = 8, 10, 12) yields quaternary ammonium surfactants **35**, which may be alkylated with 1,3-propane sultone to give **32**. If the alkylation reaction is unsuccessful in THF, the indicated solvent, a more polar, but less convenient, solvent such as dimethyl sulfoxide may be used.



Surfactants **33** may be prepared by the alkylation of **35** (n = 8, 10, 12) with **36** (m = 8, 10) as illustrated (eq 8).



Compound **36** may be obtained as shown from polyoxyethylene glycol monomethyl ethers **16**.



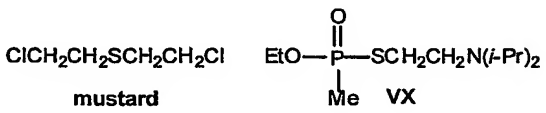
The surfactants described herein may assume various forms, including micelles and vesicles (liposomes)[32] and, in some instances, more complex supramolecular structures. The aggregate morphologies can be characterized by a combination of ^{1}H and ^{31}P NMR spectroscopy, dynamic laser light scattering (DLLS), differential scanning calorimetry (DSC), phase-contrast optical microscopy, and in-lens cryo-high resolution scanning electron microscopy (cryo-HRSEM).

The analysis of an aqueous solution/dispersion of a surfactant by ^{1}H NMR, and as appropriate by ^{31}P NMR, provides an initial indication of the size of its aggregates. Micelles and small unilamellar vesicles (SUVs), formed by sonication, generally give high resolution ^{1}H and ^{31}P NMR spectra, and larger aggregates often give spectra with significant line-broadening or the absence of signals.[33,34] The sizes of micelles and SUVs can be determined by DLLS, and those of giant vesicles (GVs),[35] formed by the hydration of surfactant thin films or smears, by phase-contrast optical microscopy. The phase transition temperatures of (vesicle) bilayers can be determined by DSC.[36] Aggregates whose morphologies cannot be determined by DLLS and optical microscopy can be subjected to cryo-HRSEM.[37]

In preliminary work,[19] it has been observed by optical microscopy that shamrock surfactant **8**, with R = Bu, n = 10, and NO_3^- exchanged for Br^-, forms the aggregates shown in Figure 1, upon the hydration of a smear in water at 23°C (size bar = 50 μm). At this time, the detailed nature of these aggregates is unclear, but it appears that they correspond to droplets of a one-component coacervate.[38]

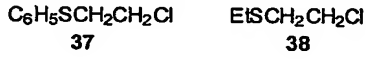
As noted above, three specific applications of several of the shamrock surfactants described herein are within the scope of the present invention. The first involves the chemical decontamination of mustard; the second involves storage and release devices and chemical switches; and the third, the remediation of heavy-metal ion-contaminated water.

Chemical Decontamination of Mustard. Chemical warfare agents such as mustard, a blistering agent, and VX, a nerve agent, continue to represent significant military and terrorist threats. A rouge nation will undoubtedly possess the capability to manufacture and use chemical weapons. This was clearly demonstrated in the 1980-98 Iran-Iraq War. And it is likely that U.S. troops were exposed to chemical agents in the 1991 Persian Gulf War. Urban terrorists represent a real threat too, as evidenced by their use of a nerve agent in the Tokyo, Japan subway in 1995. Chemical weapons are indeed insidious. They are deadly offensive weapons, and many are easy to make in large quantities by relatively straightforward, "bathtub" chemistry. Thus chemical weapons have been described as the "poor man's nuke". They will continue to be a major concern to the world for the foreseeable future.

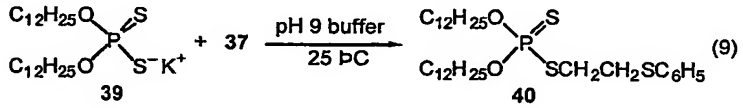


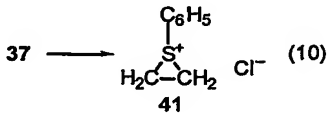
The paramount issue in dealing with chemical agents is their decontamination. There are several approaches to such decontamination.[39] In particular, chemical decontamination corresponds to the conversion of agents into nontoxic compounds by chemical reactions.[39] Reported strategies for the chemical decontamination of mustard and its simulants include nucleophilic substitution,[14,16,39,40] hydrolysis,[39,41,42] oxidation,[39,43] and elimination reactions.[39] In the work outlined below, decontamination is effected by nucleophilic substitution reactions.

Vesicles and other aggregates of dithiophosphate-based surfactants **8-10** and dithiocarbamate-based surfactants **21** and **22**, as discussed above, are expected to have utility in the chemical decontamination of mustard. Simulants **37** and **38** can be used in place of mustard itself to demonstrate such utility. A simulant generally displays the chemical and physical properties of the actual agent but is much less toxic. Immediately below, only reactions with **37** are illustrated; those with **38** are generally analogous and should be faster. The relative hydrolysis rates for **37**, **38**, and mustard are 0.095, 5.9, and 1.0, respectively, at 25°C.[44] Thus, the reactivities of **37** and **38** bracket that of mustard.

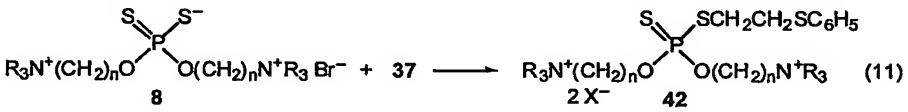


The reactions of vesicular surfactant **39** with simulants **37** and **38** (and homologues of **38** with Me or Bu substituted for Et) have previously been studied.[16,40] In each case, **39** undergoes alkylation at sulfur by the simulant, as illustrated for the reaction with **37**, which gives **40** (eq 9). The present invention also demonstrated the intermediacy of episulfonium ion **41** in this reaction, which is formed by the ionization of **37** (eq 10).[16] The nucleophilic dithiophosphate group of **39** captures **41** to give **40**.

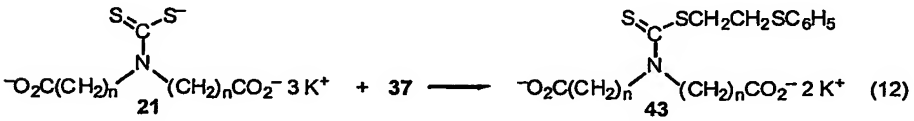




Based upon the experience of the present inventors with surfactant **39**[16,40] it is anticipated that surfactant **8** will react with **37** to give **42** (eq 11) in a process that involves the following. Simulant **37**, which is insoluble in water alone, is solubilized by aggregated **8**. At the polar aggregate-water interface, **37** ionizes to give ion **41**, which is captured by **8** to yield **42**, resulting in the chemical decontamination of simulant **37**. Derived surfactant **42** will form mixed aggregates with **8** as it is formed. It is noteworthy that the success of **8** in capturing episulfonium ion **41** results from the substantial nucleophilicity of its dithiophosphate head group.[14] The nucleophilicities of a large number of nonsurfactant species with respect to mustard have been determined.[14] The reactions of dithiophosphate-based surfactants **9** and **10** with simulant **37** (not shown) will be analogous to eq 11.

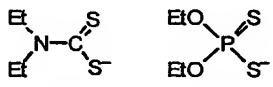


The reaction of surfactant **21** with simulant **37** to give **43** is illustrated (eq 12), and that of **22** with **37** (not shown) should proceed analogously. These reactions are expected to involve the capture of episulfonium **41** by **21** and **22**'s dithiocarbamate groups.



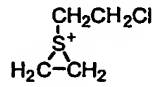
It is important to note that surfactants **21** and **22** will almost certainly be more efficient than **8-10** in decontaminating simulant **37**, based upon the reported

greater nucleophilicity of the *N,N*-diethyldithiocarbamate anion (**44**) compared to the *O,O'*-diethyldithiophosphate anion (**45**).[14] Competition factors of 34,000 and 2,600 M^{-1} have been reported[6] for **44** and **45**, respectively, relative to water (pH 8, 25°C) in the capture of **46**, the episulfonium ion derived from mustard itself. Thus **44** is more than an order of magnitude more nucleophilic than **45** with respect to **46**.



44

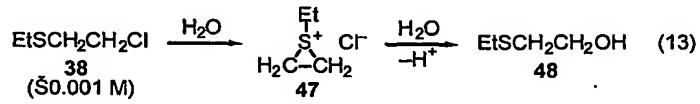
45



46

The anticipated greater nucleophilicity of the dithiocarbamate surfactants **21** and **22**, compared to **8-10**, has a significant beneficial consequence, as follows. Simulant **38** is fully decontaminated by hydrolysis in water only when it is completely converted into alcohol **48**, involving initial ionization to episulfonium ion **47**, followed by its capture by water (eq 13). However, such complete conversion occurs only when the concentration of **38** is kept low (≤ 0.001 M) and it is added to water as a concentrated solution in a polar organic solvent.[42] At higher concentrations of **38**, the system is much more complicated, because ions 49 and 50 are formed in addition to, and in greater amounts than, alcohol **48**, by the capture of episulfonium ion **47** by **48** and **38**, respectively (eq 14). Mustard itself behaves analogously, and it is believed that its analogues of **49** and **50** are responsible for the recurring toxicity of mustard in humans and in the environment.[42] [Simulant **37**, unlike **38** and mustard, hydrolyzes cleanly to the corresponding alcohol ($C_6H_5SCH_2CH_2OH$) in water, without

the accompanying formation of ions analogous **49** and **50**.[16]]



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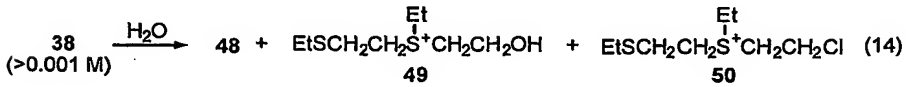
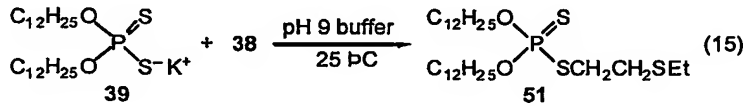


(14)

The very important practical consequence of the above is that decontamination methods for **38** (and mustard itself) must minimize, or preferably totally avoid, the formation of ions **49** and **50** (and mustard's analogues). It has been reported[40] that the reaction of equimolar amounts of **38** (0.0099 M if fully dissolved) and **39**'s SUVs gave an 89% yield of 51 (eq 15). The 11% of **38** not transformed into **51** was converted into a mixture of ions **49** and **50** and a lesser amount of alcohol **48**. The use of dithiocarbamate surfactants **21** and **22** should result in substantially more efficient decontamination of **38**, involving their alkylation reactions, with little or no concomitant formation of toxic **49** and **50**, since these surfactants are much more nucleophilic than **8-10**, as noted above.



(15)

Yang and co-workers reported[42] that in 50 vol % aqueous acetone at 20 C, the thiosulfate anion ($S_2O_3^{2-}$) reacts with simulant **38** to give **52** without the formation of any **48**, **49**, or **50**. Thus thiosulfate captures **47** to the exclusion of capture by water, **48**, or **38**, respectively. It is known that thiosulfate has a

competition factor of 27,000 M^{-1} relative to water in the capture of episulfonium ion **46**.[14] Since the competition factors for dithiocarbamate surfactants **21** and **22** are expected to be about 34,000 M^{-1} (see above), they should also react with **38** without the formation of any **48-50**.

$EtSCH_2CH_2SSO_3^-$
52

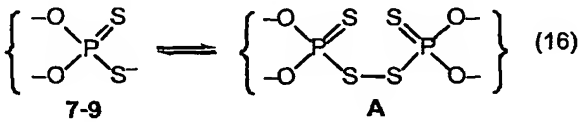
An important novel feature of decontamination with dithiophosphate surfactants **8-10** and dithiocarbamate surfactants **21** and **22**, compared to that with dithiophosphate surfactant **39** and other nucelophilic substitution methods, is that the decontaminated simulant (mustard) becomes part of a surfactant. For example, simulant **37** is converted into surfactants **42** (eq 11) and **43** (eq 12) by surfactants **8** and **21**, respectively. This feature can be exploited in water remediation as exemplified with simulant **37**. After the conversion of 37 into surfactant **42(43)**, the reaction mixture is subjected to ultrafiltration. Such a filtration would retain aggregated **42(43)**, while allowing water to pass through the filter. Overall, the decontamination process, followed by ultrafiltration, would result in remediation of water that had been contaminated with **37**.

Storage and Release Devices and Chemical Switches.

Vesicles and other aggregates derived from dithiophosphate-based surfactants **8-10** and dithiocarbamate-based surfactants **21** and **22** can be used as reversible storage and release devices, and chemical switches. There have been numerous reports of surfactant systems that can serve as storage and release

devices[45,46] and as chemical switches,[47,48] which are activated by a variety of chemical and physical processes.

Such applications of **8-10** and **21** and **22** involve their oxidation to disulfide-linked dimers A and B, respectively, and reduction back to the parent shamrock surfactants, as illustrated (eqs 16 and 17). Each oxidation involves a change in the shape and charge of the surfactant unit: $1^+ \rightarrow 4^+$ for **8** to **A**; $3^- \rightarrow 4^-$ for **9** to **A**, and for **21** to **B**; and $1^- \rightarrow 0$ for **10** to **A**, and for **22** to **B**. It is reasonable to expect that some of these redox reactions will involve a change in aggregate morphology,[34] which will form the basis for both the storage and release, and chemical switch functions. In particular, a change in morphology from closed bilayer vesicles to micelles would be appropriate for the former function.



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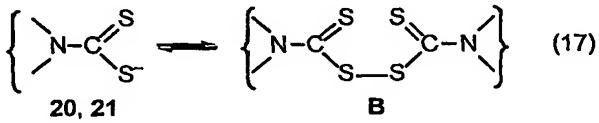
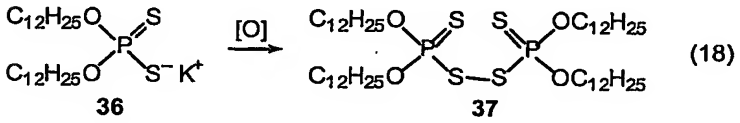


(17)

It is known that dithiophosphates and dithiocarbamates can be oxidized[30b,50] to their disulfide-linked dimers. Many oxidizing agents[50] can be used, including household bleach and hydrogen peroxide, and a variety of reducing reagents[51] can be used to effect the reverse reaction. In particular, since surfactant dimers **A** and **B** should remain in solution upon their formation (assuming T_k values of 23°C), water-soluble reducing agents such as sodium borohydride and

dithiothreitol [$HSCH_2CH(OH)CH(OH)CH_2SH$][52] can be used to convert them back to the parent shamrock surfactants. The reduction of the positively-charged dimer **A** derived from **7** (see **39** below) by the former will be facilitated by the electrostatic accumulation of BH_4^- by its positively-charged aggregates.

In preliminary work,[19] it has been demonstrated that vesicular surfactant **36** can be converted into **37** by oxidation with household bleach (NaOCl) within 10 min, or with hydrogen peroxide within 60 min at 23°C (eq 18). This conversion would result in the release of compounds entrapped within the water compartments of **36**'s vesicles, because **37**, a high-molecular weight, neutral compound, does not support vesicle formation. In fact, **37** precipitates from solution as an oil.



36 **37** (18)

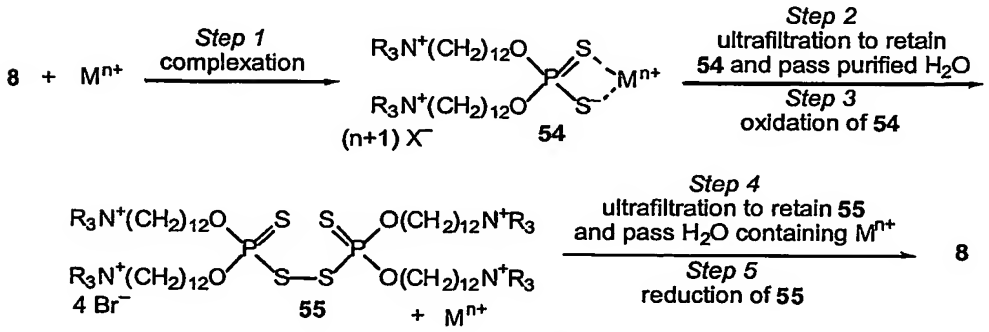
Remediation of Heavy-Metal Ion-Contaminated Water.

Metal ions have been removed from water by micellar-enhanced ultrafiltration (MEUF),[53] as well as by ligand-modified MEUF.[54,55] Generally, MEUF involves electrostatic binding of metal cations to anionic micelles of surfactants such as sodium dodecyl sulfate. Ligand-modified MEUF involves a host micelle containing a lipophilic ligand that coordinates to metal ions. Shamrock surfactants offer a different and perhaps superior type of ligand-based separation process. With them, no host surfactant is required, because the aggregate-forming surfactant also contains the ligand.

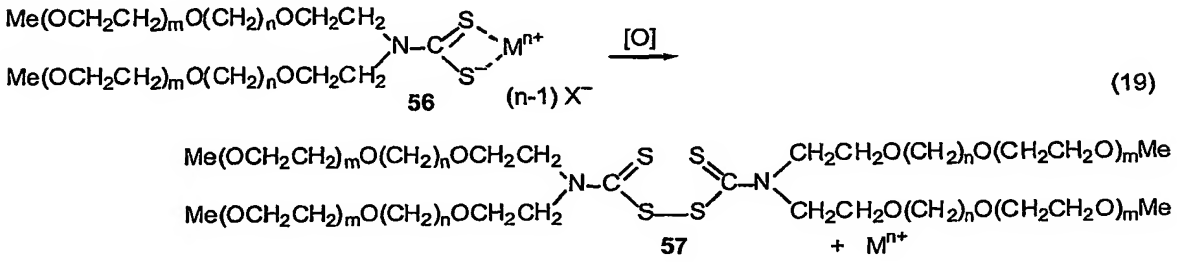
Shamrock surfactants **8**, **10**, and **22** can be used in the remediation of water (and other materials)

contaminated with heavy-metal ions (M^{n+}). The Surfactant **8** would be applied in water remediation as shown in the Scheme outlined below. Upon the addition of **8** to contaminated water, the dithiophosphate groups of *one or more* of its surfactant cations will coordinate with heavy-metal ions to form aggregated complexes **54** in *Step 1*. In *Step 2*, ultrafiltration of the system will retain the aggregated complexes, while allowing water to pass through the filter, devoid of heavy metals. The goal of water remediation can thus be achieved. Importantly, this system also provides for the recycling of **54** back to **8** for further use. Accordingly, in *Step 3*, aggregated complexes **54** will be oxidized to give (aggregated) surfactant **55**. Note that this reaction converts the coordinated, negatively-charged dithiophosphate group of **54** into the neutral disulfide-linked dithiophosphate group of **55** and releases M^{n+} in the process. Then another ultrafiltration in *Step 4* will retain aggregated **55** while allowing water containing M^{n+} to pass through the filter. Lastly, in *Step 5*, the disulfide linkage of **55** will be reduced to regenerate **8**. The oxidizing and reducing agents used in *Steps 3 and 4*, respectively, will be those used above in the storage and release, and chemical switch applications.

Scheme



The use of surfactants **10** and **22** in water remediation would be analogous to that of surfactant **8**, as exemplified below for the latter. Complex **56**, derived from one or more of **22** and M^{n+}, will be oxidized to surfactant disulfide-linked dimer **57** (eq 19), which will be reduced to regenerate **22**. The efficient complexation of heavy-metal ions by dithiophosphate[56] and dithiocarbamate[30c] groups is well known. Surfactants **9** and **21** would not be appropriate for use in water remediation, because their carboxylate groups would compete with their dithiophosphate and dithiocarbamate groups, respectively, in complexation of the heavy-metal ions.



Shamrock surfactants **8**, **10**, and **22** are expected to form complexes with ions of metals such as Cd, Cr, Co, Cu, Hg, Ni, Pb, and Zn, using the semi-equilibrium dialysis method, which has been employed in the evaluation of various ligands in ligand-modified MEUF.[54]

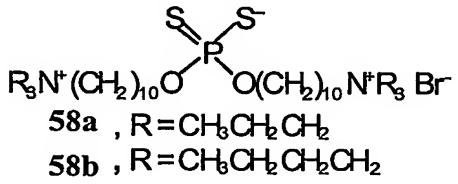
The shamrock surfactants should be useful in their applications as micelles, vesicles, or other aggregate types as appropriate. For those surfactants that form vesicles, both SUVs and GVs can be employed. Above it was noted that shamrock surfactant **7**, with R = Bu, n = 10, and NO_3^- exchanged for Br^-, may form a one-component

coacervate. A surfactant coacervate phase has been used to extract chlorinated aliphatic compounds form water.[57]

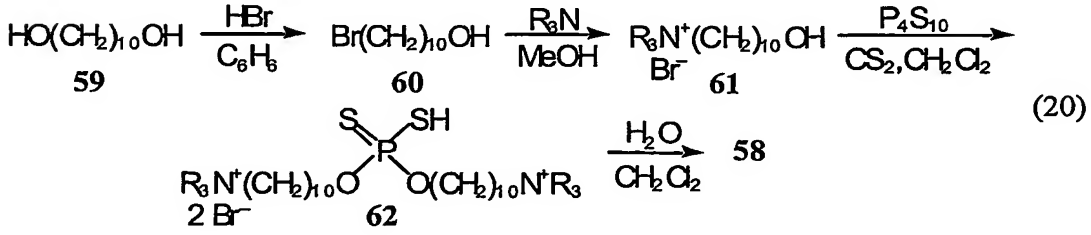
The following examples present further detail regarding the practice of the instant invention. These examples are provided for illustrative purposes only and are not intended to limit the scope of the invention in any way.

EXAMPLE 1

Shamrock surfactants **58a** and **58b** were synthesized in four steps as illustrated below (eq 20), starting with the conversion of commercially available diol **59** into bromo alcohol **60**. The nucleophilic substitution reaction of R_3N (R = $CH_3CH_2CH_2$ or $CH_3CH_2CH_2CH_2$) with **60** gave surfactants **61a** and **61b**. Then **61a** and **61b** were converted into compounds **62a** and **62b**, respectively, by reaction with phosphorus pentasulfide. Finally, dichloromethane solutions of **62a** and **62b** were washed with water to give **58a** and **58b**, respectively. In this process, the dithiophosphoric acid units of **62a** and **62b** undergo ionization, with the net loss of HBr.



58a , R=$CH_3CH_2CH_2$
58b , R=$CH_3CH_2CH_2CH_2$



(20)

Experimental Section

General Procedures. ^{1}H (400 MHz) and ^{13}C (100.6 MHz) NMR spectra (23° C) were recorded in the following solvents with the indicated internal standards (relative to Me_4Si): $CDCl_3$, residual $CHCl_3$ (δ 7.27) and $CDCl_3$ (center line at δ 77.00), respectively; CD_2Cl_2, residual $CHDCl_2$ (center line at δ 5.32) and CD_2Cl_2 (center line at δ 54.00), respectively; D_2O, residual HOD (δ 4.80) for ^{1}H NMR. ^{31}P NMR (162.1 MHz) spectra were recorded in CD_2Cl_2 and D_2O with 85% H_3PO_4 as external standard. Electrospray (ES) mass spectra (positive ion mode) of surfactants **58** were obtained on a Thermo-Finnigan LCQ instrument.

10-Bromo-1-decanol (60). A modified literature procedure[58] was used to convert 17.4 g (0.100 mol) of commercially available 1,10-decandiol (**59**) into 23.0 g of crude product. This material was column chromatographed on silica gel with elution by 1:5 (v/v) ethyl acetate-hexane to give 18.2 g (77%) of **60** as a wax: ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.65 (t, 2H, CH_2O), 3.42 (t, 2H, CH_2Br), 1.86 (p, 2H, CH_2CH_2Br), 1.57 (p, 2H, CH_2CH_2O), 1.35 (m, 13H, OH, $(CH_2)_6$); ^{13}C NMR (100.6 MHz, $CDCl_3$) δ 63.28, 34.30, 32.98, 29.91, 29.71, 29.68, 29.59, 28.94, 28.36, 25.92.

10-Hydroxy-*N*,*N*,*N*-tripropyldecan-1-aminium Bromide (61a). A modified literature procedure[59] was used. A mixture of 32.83 g (22.91 mmol) of tripropylamine, 5.44 g of **60**, and 150 mL of C_2H_5OH was refluxed for 5 days and then rotary evaporated. A solution of the residue in 50 mL of H_2O was extracted with two 30-mL portions of Et_2O and then 25 mL of ethyl acetate. The aqueous solution was adjusted to pH ca. 10 with solid K_2CO_3 and extracted with two 30 mL-portions of diethyl ether. After H_2O was

removed by rotary evaporation, 60 mL of $CHCl_3$ was added to the residue, and the resultant mixture was filtered and rotary evaporated to give 7.88 g (90%) of **61a** as wax: ^{1}H NMR (100.6 MHz, D_2O) δ 3.57 (t, 2H, CH_2O), 3.14 (m, 8H, $(CH_3CH_2CH_2)_3N^+CH_2$), 1.67 (m, 8H, $(CH_3CH_2CH_2)_3N^+CH_2CH_2$), 1.52 (m, 2H, CH_2CH_2O), 1.40 (m, 12H, $NCH_2CH_2(CH_2)_6$), 0.92 (t, 9H, 3 CH_3); ^{13}C NMR (100.6 MHz, D_2O) δ 61.69, 59.60, 58.25, 31.07, 28.31, 28.26, 28.18, 27.92, 25.29, 24.83, 20.77, 14.65, 9.64; IR (NaCl) 3275 (br), 2916 (vs), 1659 (m), 1487 (s), 1381 (s), 1057 (s), 1007 (m), 965 (m), 763 (m), 634 (m) cm^{-1}. Anal. Calcd for $C_{19}H_{42}BrNO\cdot 0.5H_2O$: C, 58.60; H, 11.13. Found: C, 58.32; H, 10.86.

10-Hydroxy-*N,N,N*-tributyldecan-1-aminium Bromide (61b). The procedure for surfactant **61a** was used, starting with a reaction mixture of 60.29 g (0.325 mol) of tributylamine, 7.76 g of **60**, and 200 mL of C_2H_5OH, which gave 12.0 g (87%) of **61b** as a wax: ^{1}H NMR (100.6 MHz, D_2O) δ 3.62 (t, 2H, CH_2O), 3.22 (m, 8H, $(CH_3CH_2CH_2CH_2)_3N^+CH_2$), 1.67 (m, 8H, $(CH_3CH_2CH_2CH_2)_3N^+CH_2CH_2$), 1.57 (m, 2H, CH_2CH_2O), 1.40 (m, 18H, $(CH_3CH_2CH_2CH_2)_3N^+CH_2CH_2(CH_2)_6$), 0.98 (t, 9H, 3 CH_3); ^{13}C NMR (100.6 MHz, D_2O) δ 61.75, 58.12, 57.97, 31.12, 28.32, 28.16, 27.88, 25.26, 24.87, 23.01, 20.75, 19.02, 12.70; IR (NaCl) 3321 (br), 2959 (vs), 2927 (vs), 2856 (vs), 1486 (s), 1381 (m), 1058 (s), 883 (m), 747 (m) cm^{-1}. Anal. Calcd for $C_{22}H_{48}BrNO\cdot 0.5H_2O$: C, 61.23; H, 11.45. Found: C, 61.54; H, 11.37.

***O,O'*-Di-[10-(*N,N,N*-tripropylammonio)decyl] phosphorodithioate Bromide (58a).** A solution of 0.250 g (0.657 mmol) of surfactant **61a**, 0.0370 g (0.0821 mmol) of phosphorus pentasulfide, 4.0 mL of CS_2, and 8.0 ml of CH_2Cl_2 was refluxed under N_2 for 2 h and then rotary

evaporated. A solution of the residue in 20 mL of CH_2Cl_2 was washed with 3 mL of water, dried, and rotary evaporated to give 0.20 g (79%) of **58a** as a light yellow oil: ^{1}H NMR (400 MHz, CD_2Cl_2) δ 3.87 (q, 4H, 2 CH_2O), 3.25 (m, 16H, 2 $(CH_3CH_2CH_2)_3N^+CH_2$), 1.71 (m, 20H, 2 $(CH_3CH_2CH_2)_3N^+CH_2CH_2$, 2 CH_2CH_2O), 1.33 (m, 24H, 2 $NCH_2CH_2(CH_2)_6$), 1.04 (t, 18H, 6 CH_3); ^{13}C NMR (100.6 MHz, CD_2Cl_2) δ 65.23, 61.24, 59.99, 29.11, 29.06, 28.93, 28.75, 26.70, 25.97, 22.60, 16.37, 11.18; ^{31}P NMR (162.1 MHz, CD_2Cl_2) δ 114.66; IR (NaCl) 3322 (br), 2928 (vs), 1657 (m), 1473 (vs), 1387 (s), 1273 (m), 964 (s), 851 (m), 799 (m), 730 (s), 681 (vs), 632 (m) cm^{-1}. Anal. Calcd for $C_{38}H_{82}N_2O_2PS_2Br \cdot 1.5H_2O$: C, 56.97; H, 10.69. Found: C, 56.84; H, 10.54. ES MS (methanol) calcd for $C_{38}H_{82}N_2O_2PS_2$ (surfactant cation) 693.6, found 693.5.

***O,O'*-Di-[10-(*N,N,N*-tributylammonio)decyl] phosphorodithioate Bromide (58b).** The same general procedure used for surfactant compound **58a**, as described above, was repeated, starting with a reaction mixture of 1.52 g (3.6 mmol) of surfactant **61b**, 0.200 g (0.45 mmol) of phosphorus pentasulfide, 10.0 mL of CS_2, and 20.0 mL of CH_2Cl_2, which gave 1.10 g (71%) of **58b** as a yellow oil: ^{1}H NMR (CD_2Cl_2) δ 3.87 (q, 4H, 2 CH_2O), 3.27 (m, 16H, 2 $(CH_3CH_2CH_2CH_2)_3N^+CH_2$), 1.64 (m, 20H, 2 $(CH_3CH_2CH_2CH_2)_3N^+CH_2CH_2$, 2 CH_2CH_2O), 1.41 (m, 36H, 2 $(CH_3CH_2CH_2CH_2)_3N^+CH_2CH_2(CH_2)_6$), 1.01 (t, 18H, 6 CH_3); ^{13}C NMR (100.6 MHz, CD_2Cl_2) δ 65.28, 59.93, 59.60, 30.78, 29.18, 29.03, 28.90, 26.76, 26.07, 24.70, 23.52, 22.70, 20.37, 14.04; ^{31}P NMR (162.1 MHz, CD_2Cl_2) δ 115.53; IR (NaCl) 2932 (vs), 2856 (vs), 1741 (vs), 1338 (vs), 1172 (m), 1109 (m), 1031 (s), 1003 (s), 883 (s), 830 (s), (s), 738 (s), 682 (vs), 667 (s), 617 (m) cm^{-1}. Anal. Calcd for $C_{44}H_{94}N_2O_2PS_2Br \cdot 2H_2O$: C, 59.10; H, 11.05. Found: C,

59.15; H, 10.80. ES MS (methanol) calcd for $C_{44}H_{94}N_2O_2PS_2$ (surfactant cation) 777.6, found 777.6.

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A number of literature references are cited in the foregoing application in order to more fully describe the state of the art to which this invention pertains. The entire disclosure of each of these citations is incorporated by reference herein.

While certain embodiments of the present invention have been described and/or specifically exemplified above, various other embodiments will be apparent to those skilled in the art from the foregoing disclosure. The present invention is, therefore, not limited to such embodiments, but is capable of considerable variation and modification without departing from the scope of the following claims.